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Dielectric Properties of Beans at Ultra-Wide Band Frequencies

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ABSTRACT

Dielectric properties of three varieties of common beans (*Phaseolus vulgaris* L.) were determined at Ultra-Wideband (UWB) frequencies (3-10.6 GHz) using a free space transmission method. Beans were conditioned to get different moisture contents; the bulk density of beans (ρ) increased at higher moisture contents. Permittivity and conductivity of beans also increased with moisture content. The dielectric constant (ε') remained practically constant in the studied frequency range, while loss factor (ε") decreased in frequency. The ε'/ρ vs ε''/ρ complex-plane plot (Argand diagram) was built and a linear trend was observed, with positive slope. However, this slope value decreased at higher frequencies.

KEYWORDS: Dielectric properties, free space transmission method, ultra-wide band, beans.

INTRODUCTION

Mexico is the country with the largest diversity of beans, *Phaseolus vulgaris* L. [Bebert et al., 2002], with more than 142 varieties, which include common and native species [Rodríguez-Licea et al., 2010] with around 20% of protein. Beans are widely cultivated and consumed in the country. The preference of a specific variety depends on the country region [Rodríguez-Licea et al., 2010], being the clear and black types highly commercialized. Moisture content in beans is very important, as it may affect operations such as handling, storage, or processing. According to Mexican Specifications [NMX, 2002], the adequate moisture content should be between 9 and 13% (wet basis) for storage, commercialization and processing. Low moisture content would result in a harder crop with longer cooking times, while high levels will promote mold growth.

Dielectric properties are valuable parameters for biological products [Içier and Baysal, 2004]. Data for diverse legumes have been reported, such as soybean [Mane and Puri, 2008]; chickpea, green pea, lentil and soybean flours [Guo et al., 2010], and for blackeyed peas and mung beans flours [Jiao et al., 2011]. The dielectric properties of *Campeão*-3 Brazilian beans at a very low frequency (10-100 MHz) have been reported [Berbert et al., 2002], showing dependence on frequency and density. However, no study of any variety of Mexican beans has been reported in the literature.

There are several methods to determine dielectric properties in agricultural and food products [Içier and Baysal, 2004; Venkatesh and Raghavan, 2005]. Among them, the open ended coaxial-line method is widely employed, however it requires contact with the material to be characterized [Nelson et al., 1996]. The free space transmission method has the advantage of being contactless, non-invasive and non-destructive [Trabelsi et al., 1997]; the method uses measurements of radiating fields employing two antennas [El Sabbagh et al., 2003].

The objective of this study is to determine the dielectric properties of selected varieties of Mexican beans at different moisture content employing the free space transmission method. The designed system operates in the full Ultra Wide Band (UWB) spectrum (3-10.6 GHz), which has been allocated recently by the FCC [Kataria et al., 2009].

MATERIALS AND METHODS

Beans

Three varieties of Mexican common beans (*Phaseolus vulgaris* L.) were studied: '*Flor de mayo*', '*Bayo*' and '*Negro*', shown in Figure 1. Beans were conditioned to different moisture contents. To decrease the moisture content, they were placed in an electrical oven at 60 °C for 1 or 3 h. To increase the moisture content, beans were placed in glass jars with double bottom, using tap water to saturate the environment; this condition was maintained for 9 h at room temperature. The moisture content was determined following the official method 950.46 [AOAC, 2000]. Bulk density of beans was calculated by the weight of 500 mL of legumes [Mohsenin, 1986].

(a)

(b)

(c)

Figure 1. Aspect of the three studied varieties of Mexican beans: (a) '*Flor de mayo*', (b) '*Bayo*', and (c) '*Negro*'.

Antenna design and characterization

Tapered planar antennas are known to have a very wide response [Colin-Beltran et al., 2013]. In order to cover the whole UWB frequency range, elliptical tapered antipodal 66 Vivaldi antennas were designed and built for the measurement system. Figure 2 shows the antenna geometry and the coordinate system. A smooth transition between tapered slot and microstrip is used in the antipodal Vivaldi antenna. The microstrip line and its ground plane are on different sides of the

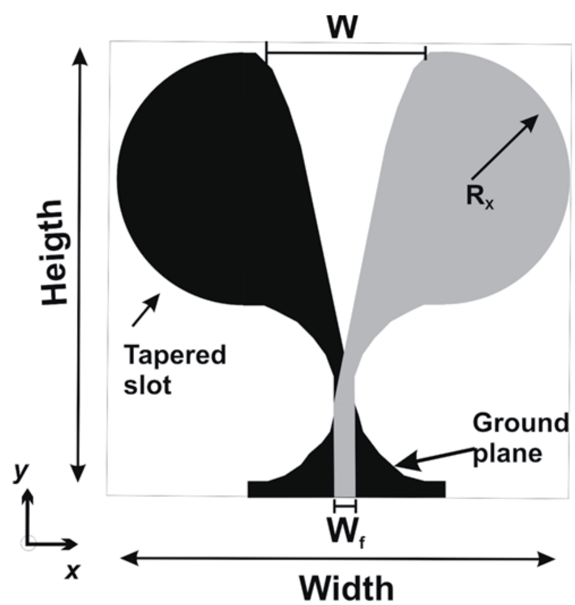

Figure 2. Geometry of the eliptical tapered antipodal Vivaldi antennas for the dielectric properties measurement system.

substrate and gradually flare out in opposite directions to form the tapered slot. The tapered slot is an exponential transition with an opening rate b; the curve is defined by the Equation (1):

$$y = C_1 e^{bx} + C_2 \qquad (1)$$

where C_1 and C_2 were determined by the coordinates of the first and last points of the exponential curve [Wang et al., 2007]; finally, x and y are the ordered pairs in the Cartesian plane.

Two elliptical extensions with R_x axis radius were added at the ends of radiators to reduce reflection from the straight edges. As the Antipodal antennas operate as a resonant antenna at the lower end of frequency band, the aperture antenna width W was determined based on the lowest frequency, f_{min} , and the effective dielectric constant of the substrate, ε_{eff} in Equation (2):

$$W = \frac{c}{2f_{\min}\sqrt{\varepsilon_{eff}}} \qquad (2)$$

Also, a 50 Ω microstrip line with a width W_f=3.5 mm is used to feed the antenna. The substrate used for the design is 1.58-mm-thick, with relative permittivity ε_r=3.5 (Rogers Corporation, USA). The final antenna dimensions are shown in the Table I.

Table I. Final antenna parameters design (all in mm).

W	*R_x*	*Height*	*Width*	*W_f*
32	24	80	80	3.5

The reflection coefficient of the antenna was measured using a vector network analyzer (SPARQ-3002E, Lecroy, USA).

Figure 3 shows the simulated and experimental return loss (S11) of the antenna, which is better than 10 dB from 2.5 to 12 GHz. Simulation was carried out by using the HFSS software (version 13, ANSYS, USA).

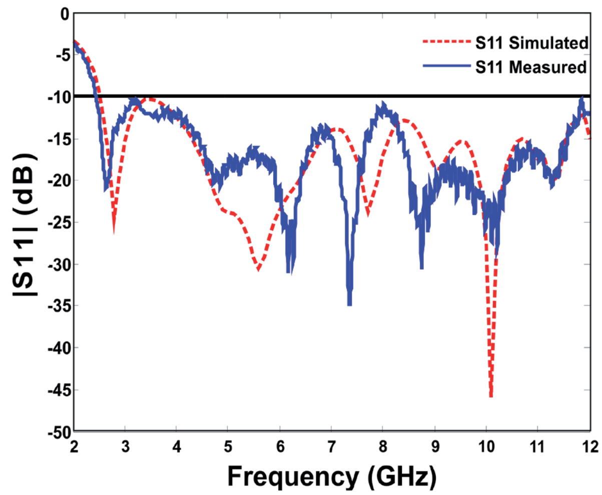

Figure 3. Measured and simulated return loss of the elliptical tapered antipodal Vivaldi antenna.

Dielectric proprieties measurements

The characterization method based on the measurement of an insertion function using radiant fields [Muqaibel and Safaai-Jazi, 2003] was employed for obtaining the dielectric properties and the conductivity of the beans. Figure 4 shows the experimental set-up to obtain the insertion function. The insertion function was obtained through two frequency domain measurements using a vector network analyzer in the full UWB frequency range (3.1-10.6 GHz) at 19 °C.

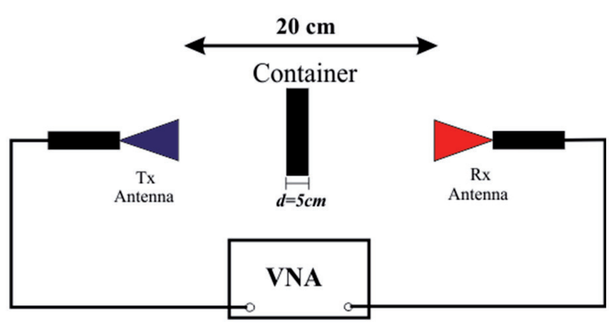

Figure 4. Schematic diagram of the dielectric properties measurements system.

Two wide band Vivaldi antennas, one as a transmitter and the other as a receiver, were separated by 20 cm. The bean sample (around 1.3 kg) was placed between the antennas in a cardboard box container with (25 cm height, 11 cm width and 5 cm thickness) (*d*).

The measurement system was placed within a microwave anechoic chamber, which provides a low reflection environment for accurate characterization. The sample was assumed to be in the form of a slab with thickness d. First, the transmission coefficient with an empty container was measured, and then, the container full of beans. The insertion transfer function was calculated as [Muqaibel and Safaai-Jazi, 2003]:

$$H(f) = \frac{S_{21}(f)}{S_{21}^{ec}(f)} \tag{3}$$

where S_{21} is the transmission reflection coefficient when the container is full of beans. is the transmission reflection coeffici S_{21}^{ec} with the empty container, and *f* is the frequency (Hz).

Once the insertion transfer function was calculated per Equation (3), the permittivity (ε') and loss factor (ε'') were obtained for a low loss material ($\varepsilon'' \ll \varepsilon'$) using the equations [El Sabbagh et al., 2003]:

$$\varepsilon' = \left[1 + \frac{\Delta\phi\lambda_0}{360\, d}\right]^2 \tag{4}$$

$$\varepsilon'' \approx \left(\frac{|\Delta A|\lambda_0\sqrt{\varepsilon'}}{8.686\, \pi d}\right) \tag{5}$$

where Δø is the angle of the transfer insertion function (degrees), ΔA is the attenuation in transmission due to the present of the sample (dB), λ_0 is the free-space wavelength (m), d is the thickness of the sample (m). The electrical conductivity (σ, S/m) was calculated from [Trabelsi and Nelson, 2003]:

$$\sigma = \omega\, \varepsilon''\varepsilon_0 \tag{6}$$

where ε_0 is the permittivity of the free space (8.85418782 × 10^{-12} F/m), ω is angular frequency (rad/s), $\omega = 2\pi f$.

RESULTS

Performance of the dielectric properties measurement system

The performance of the system was firstly verified by measuring the permittivity of a solid plastic foam of known dielectric constant (ε'=1.0), and 25 x 25 x 5 cm^3. The measured results gave a maximum error of 6.97% at 9.45 GHz.

Moisture content and density values of beans

Four different levels of moisture content were achieved for each bean variety. The bulk densities for '*Flor de mayo*' were 762.5, 757, 755.5, and 741.6 kg/m^3 for beans with moisture content of 5.1, 8.4, 11.2 and 13.6% (w.b.), respectively.

For '*Bayo*' variety, the densities were lower, being 730.6, 727.5, 725.2 and 722.16 kg/m^3 for 4, 7.3, 9.6 and 12.2% respectively; while for '*Negro*', the obtained values were the highest: 796.8, 790.6, 789 and 786.36 kg/m^3 for 4.5, 7.3, 9.8 and 12% (w.b.), respectively.

Frequency-dependent dielectric properties of beans

The measurements were more accurate in the range of 4.5 to 10.6 GHz for the developed system, thus, plots are shown in this interval. For punctual data, selected results are shown at 5.0, 6.85 and 10 GHz. ε' remained practically constant with the frequency in the studied range (Figure 5), while ε'' decreased (Figure 6).

The electrical conductivity increased with frequency and moisture content, with ranges of 0.2- 0.43 S/m for '*Flor de mayo*', 0.2 - 0.42 S/m for '*Bayo*', and 0.21 - 0.49 S/m for '*Negro*' (Table II). Higher ε'' and conductivity were observed for '*Flor de mayo*' and '*Negro*' varieties than the observed for '*Bayo*'.

For no pure materials, where there is a distribution of relaxation times, the Cole-Cole relation can be employed [Içier and Baysal, 2004]. The Cole-Cole or Argand

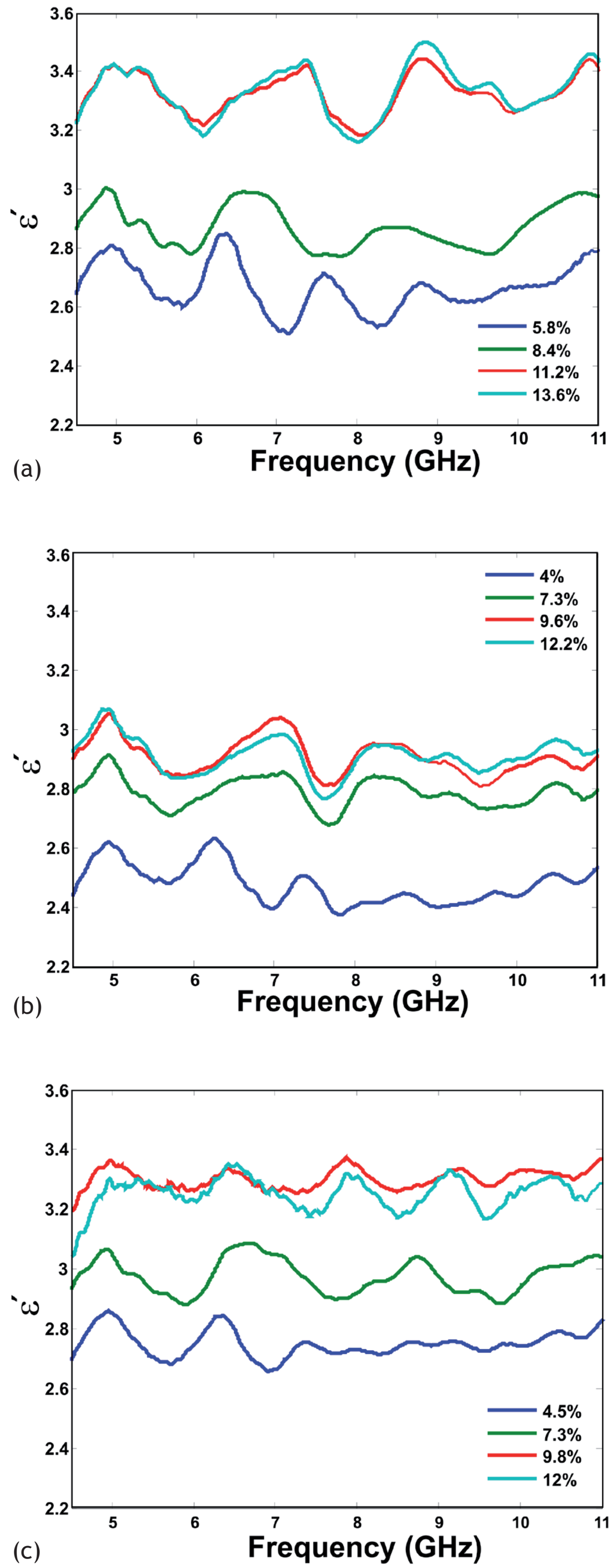

Figure 5. Dielectric constant (*ε*') of the (a) '*Flor de mayo*', (b) '*Bayo*', and (c) '*Negro*' beans, with respect to frequency.

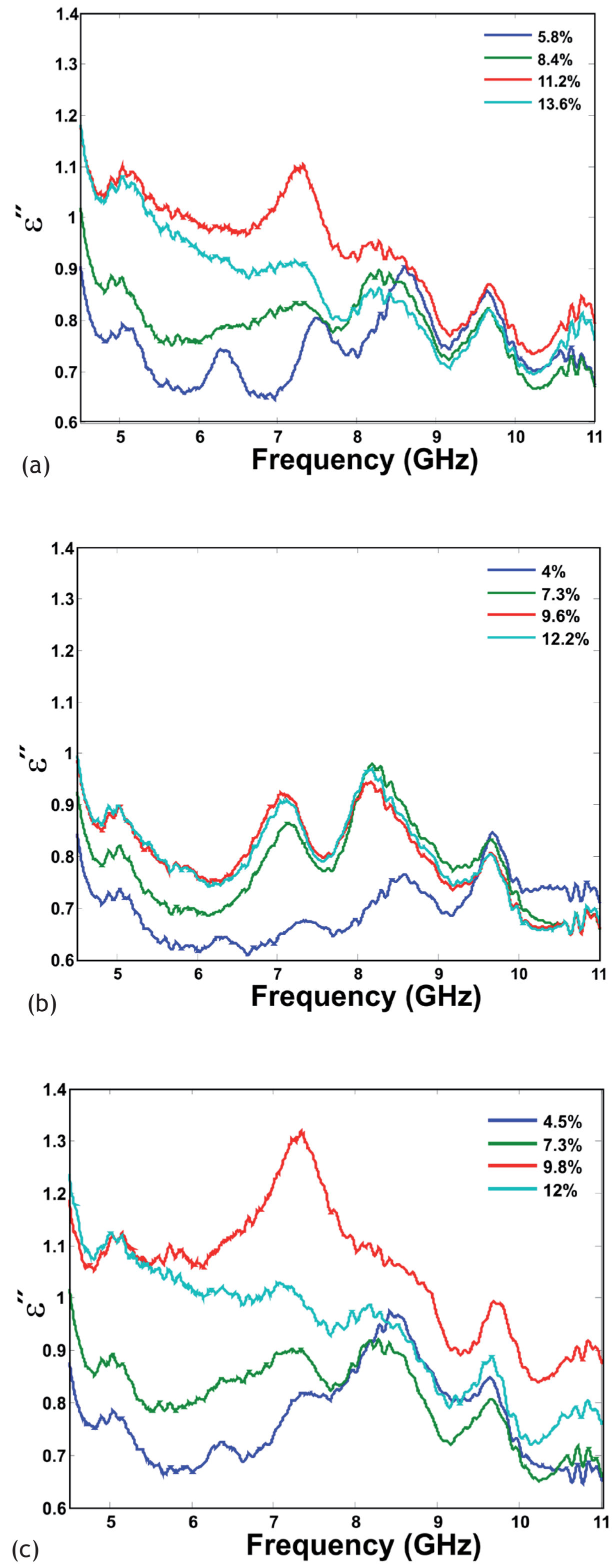

Figure 6. The loss factor (*ε*") of the (a) '*Flor de mayo*', (b) '*Bayo*', and (c) '*Negro* beans', with respect to frequency.

Table II. Electrical conductivity of three varieties of beans at different moisture contents.

Frequency (GHz)	Electrical conductivity (S/m)											
	'Flor de Mayo'				*'Bayo'*				*'Negro'*			
	5.8%	8.4%	11.2%	13.6%	4.0%	7.3%	9.6%	12.2%	4.5%	7.3%	9.8%	12.0%
5	0.217	0.245	0.302	0.297	0.203	0.227	0.247	0.249	0.215	0.246	0.309	0.313
6.85	0.247	0.308	0.38	0.341	0.239	0.304	0.333	0.325	0.271	0.327	0.445	0.38
10	0.416	0.402	0.435	0.411	0.418	0.402	0.389	0.387	0.403	0.392	0.498	0.414

diagram plots the dielectric constant and dielectric loss in the complex plane, and it is useful to analyze the dielectric behavior of materials. Trabelsi et al., [2001] have proposed to represent the Argand diagram for samples with different moisture contents plotting the dielectric properties divided by the bulk density. Figure 7 shows the Argand diagram for the studied beans at three different frequencies (5, 6.85 and 10 GHz). The complex relationship between ε' and ε'' is linear with increasing frequency. The slope of the straight line decreases with the increasing frequency.

Effect of moisture content of beans in dielectric properties, Figures 8 and 9, show the variation of the dielectric properties of beans with moisture content. The dielectric constant increases linearly up to about 10-11% of moisture content for the three varieties, after that, ε' remains almost constant. Similar trends were observed for the whole range of frequencies.

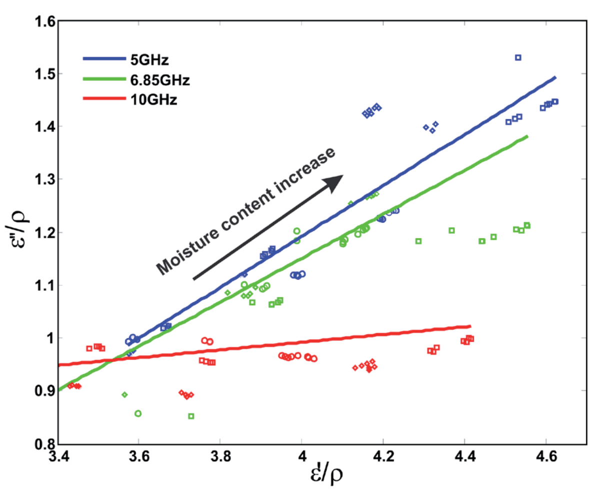

Figure 7. Argand diagram for beans at selected frequencies and 19 °C.

For bean loss factor, there is a linearly increasing trend respect to moisture content up to 10-11% as well, but only for frequencies below 7 GHz. For higher frequencies (as example see 10 GHz in Figure 9), there is not effect of the moisture content on the loss factor. For higher frequencies, the loss factor remains practically constant with values between 0.70 to 0.75 for the studied varieties.

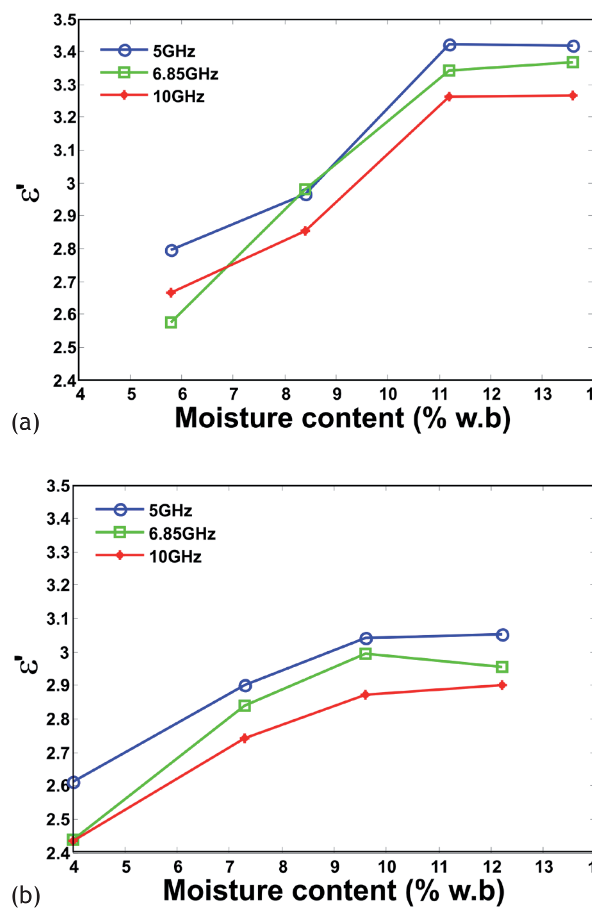

Figure 8. Variation of dielectric constant (ε') with moisture content of (a) *'Flor de mayo'* and (b) *'Bayo'* beans at selected frequencies.

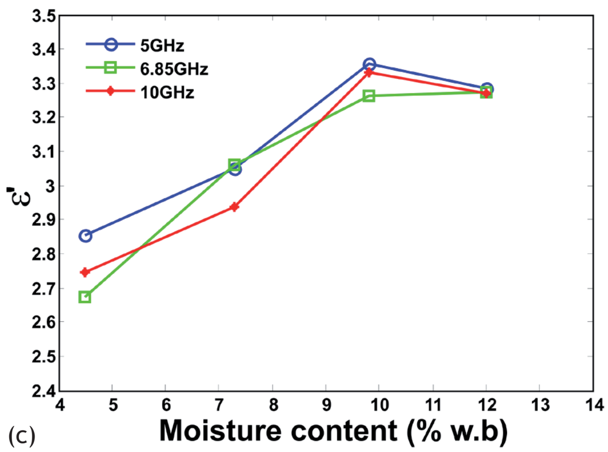

Figure 8. (c) Variation of dielectric constant (ε') with moisture content of '*Negro*' beans at selected frequencies.

DISCUSSION

The performance of the developed system for measurement of the dielectric properties of beans is considered acceptable. Trabelsi et al., [1992] calculated a relative error of 3% for ε' for their measurement system based on horn antennas. Wang et al., [2003] reported typical error of 5% for an open ended coaxial probe system, with maximum error of 18.7% for ε' when butyl alcohol was measured.

'*Negro*' variety had the highest density, followed by '*Flor de mayo*' and '*Bayo*'. The bulk density of common beans decreased as moisture content increased. This trend is well-known and also reported for other legumes, such as chickpea, lentil and green pea [Guo et al., 2010]. The density values of beans in our study are in the range reported by Berbert et al., [2002] for beans of the Campeão-3 variety, who reported densities between 650 and 850 kg/m^3, depending on moisture and determination method. De Lucia and Assennato [2013] reported density values of 750-850 kg/m^3 for beans in general. '*Negro*' and '*Flor de mayo*' varieties were found in that interval. The complex permittivity is affected by bulk density, even in similar way than water [Trabelsi et al., 1999]; thus, it is very important to have knowledge of this property when dielectric properties are studied.

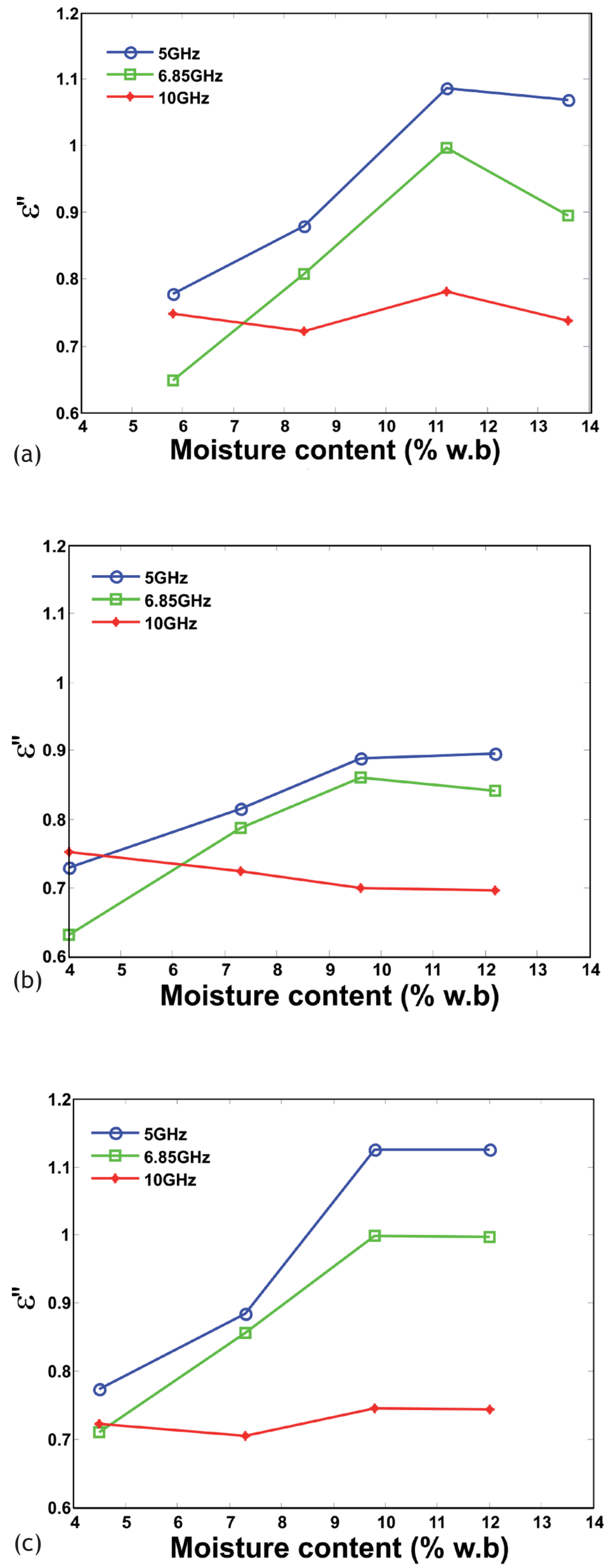

Figure 9. Variation of loss factor (ε") with moisture content of (a) '*Flor de mayo*', (b) '*Bayo*', and (c) '*Negro*' beans at selected frequencies.

ε' for soybean with 4.3% of moisture content had a value of 2 in the range of 13-18 GHz [Mane and Puri, 2008], which is lower than ε' values for the common beans of our study. Both dielectric constant and loss factor were more affected when moisture content was low. To relate complex permittivity with moisture content, the adequate frequency should be 5 or 6.75 GHz, as at 10 GHz effects of frequency are not marked.

Electrical conductivity values of beans were low at room temperature, as it is reported for other legumes [Mane and Puri, 2008; Guo et al., 2010]. However, values in our study are quite high due to high frequencies.

The trends observed for frequency and moisture content in the Argand diagram are in agreement with the complex plane represented for other grains and legumes, such as corn [Trabelsi et al., 1998]; chickpea, green pea and lentils [Guo et al., 2010]; and peanuts [Trabelsi et al., 2013]. The three studied varieties follow similar tendencies, and it was possible to group them in the same plot for complex permittivity.

CONCLUSION

Free space transmission method is a good tool for determining dielectric properties of beans. At UWB frequency range, bean dielectric properties were dependent on frequency. Moisture content affected the dielectric properties of beans, especially at levels below 10%.

Through the Argand diagram, it can be concluded that there are similar trends in dielectric properties for the studied varieties, with increasing values as moisture content increases.

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